Effect of VLBI Observation Network on Source Stability

Karine Le Bail [1], David Gordon [1]

Abstract The observing network changes depending on the type of session and the availability of stations. Some factors that affect the session network are the nature of the session (geodesy, astronomy), the strength and/or the location of the target sources, and the maintenance or repair of certain antennas. The observation frequency varies from weekly (R1 and R4 sessions) to a few irregular times a year (R&D, CRF, and CRDS sessions). Because of such network disparities and irregularities, a given source is observed irregularly and we expect its time series to reflect some non-stationarity. This study aims at investigating the question: Does the observing network have an effect on source stability?
We isolated position determination depending on different types of sessions and determined the type and level of noise using the Allan variance. We show the results particularly for the source 3C418, emphasizing on the differences between R1 and R4 sessions. The source 3C418 is one of the sources used regularly in geodesy sessions. It was initially chosen because it was a strong and compact source. In the last part of this paper, we show the temporal change in behavior in its time series over the past two years. This demonstrates the importance of observing and monitoring all sources regularly.

Keywords Radio source position time series, statistical characterization, Allan variance

1. NVI, Inc./NASA Goddard Space Flight Center, USA

1 Introduction

The problem we face in VLBI is the continuous evolution of the entire system we study: the radio sources are evolving, the observing instrument or data are changing with time, and the sampling is not homogeneous.

Le Bail and Gordon 2010 [1] and Le Bail et al. 2014 [2] discussed the source 3C418 and showed that the source exhibits different statistical characteristics depending on the studied time period. When considering the period 1988–1993, the noise of the source position time series is a flicker noise at a one-year level of 180 µas for right ascension (R.A.) and 300 µas for declination (DEC). When considering the period 1997–2005, the noise is a white noise at a one-year level of 70 µas for R.A. and 110 µas for DEC. One cause could be the technique and analysis improvement over the years such as improvements to the instrumentation or data processing. A second cause is that the source may change with time.

Another cause for inhomogeneity is the network. From one observation to another, the source is observed by different stations. We investigate how this impacts the source position determination. We studied different sources but decided to focus on 3C418. In Section 2, we extract from its position time series the points corresponding to the same type of sessions (e.g., R1, R4, RDV). In Section 3, we study the different extracted time series with the Allan variance and determine the type and level of noise. Section 4 is a discussion on the change of the behavior of 3C418 in the past two years and presents a tool that could help monitor all VLBI sources to detect such changes.

2 The Example of the Source 3C418 in Various Sessions since 2002

The set of VLBI position time series we analyzed in this paper was produced with the Calc/Solve software at GSFC. It used VLBI sessions from August 3, 1979 through March 26, 2018, for a total of 6,182 sessions, including all of the VCS1-6, VCS-II, and UF001 A-T/UG002 A-C VLBA sessions. It contains 4,529 sources, including the VCS sources.

There are significant variations in the number of sessions per source: 222 sources were observed successfully in only one session, 3,569 sources in five or less sessions, and 3,747 sources in less than ten sessions. Only 782 sources, 17% of the set, were observed in ten or more sessions. Some sources have a long observation history like OJ287 (4,361 sessions covering the period April 1980 to March 2018) and 0552+398 (4,589 sessions covering the period August 1979 to March 2018).

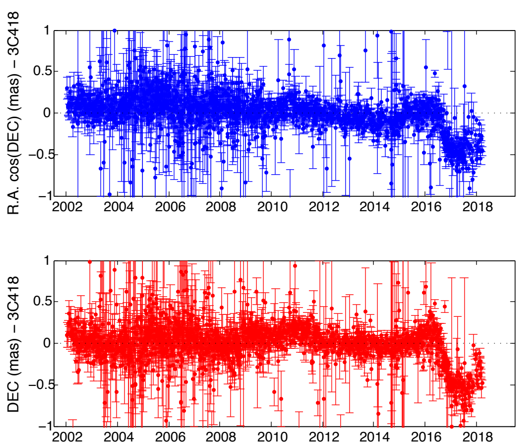

Fig. 1 Position time series of the source 3C418 over the period January 2002 to March 2018.

In this study, we will focus on the source 3C418. This source was observed in 1,969 sessions total during the period from June 1982 to March 2018. Since we are interested in the weekly IVS sessions R1 and R4, we restrain the studied period to January 2002 to March 2018 which represents 1,621 sessions (see Figure 1).

Over this period, 3C418 was observed in 592 R1 sessions, 618 R4 sessions, 75 R&D sessions, 51 RDV sessions, 55 EURO sessions, 20 APSG sessions, 11 AOV sessions, 63 T2 sessions, two AUA sessions, two AUG sessions, and 127 various others. We show the position time series obtained when extracting points corresponding to R1, R4, and RDV sessions in Figure 2.

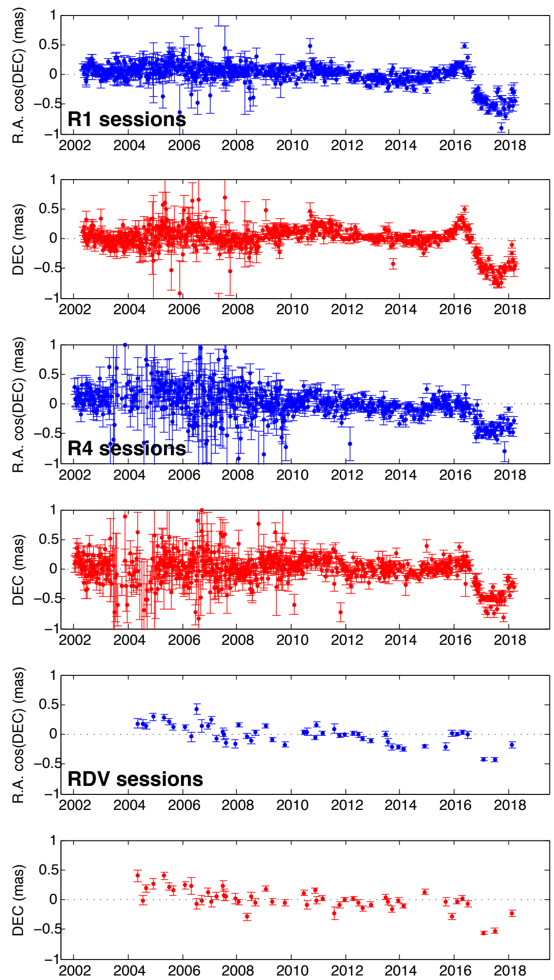

Fig. 2 Position time series of the source 3C418 differentiated by type of sessions (top two plots: R1 sessions, middle two plots: R4 sessions, bottom two plots: RDV sessions) over the period January 2002 to March 2018.

The three time series show the same behavior for the source, even though the formal errors of the R4 sessions are generally larger than the formal errors of the R1 sessions, which are larger than the RDV formal errors. This could be explained by the number of observations per session: the average number of observations used to estimate the position for each session is 84 for the R4 sessions, 171 for the R1 sessions, and 275 for the RDV sessions. The time series, obtained when extracting only R1 or R4 sessions, have more points than the time series of RDV sessions, which allows the access to more details.

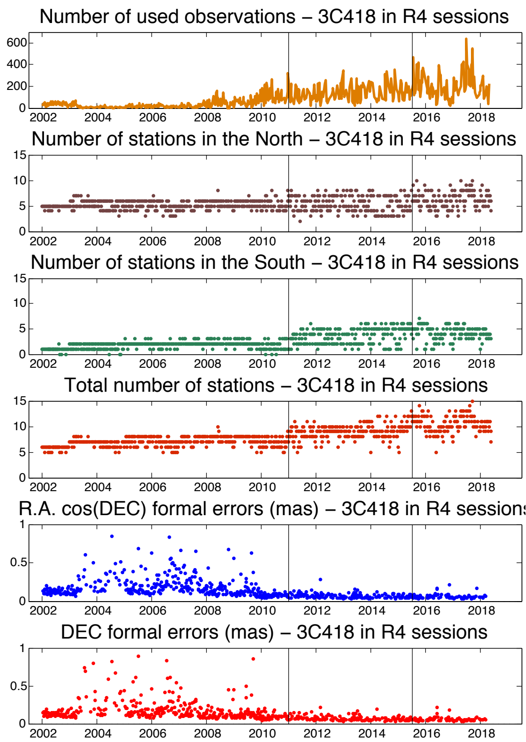

Fig. 3 Observation numbers (top), station numbers (center), and formal errors of the source 3C418 in R4 sessions from 2002 to 2018.

The position formal errors for the R1 and R4 sessions improve over time. If we look at the R4 sessions specifically (see Figure 3), the number of used observations in the solution increase significantly, while the formal errors decrease. The increase in the number of observations is partially explained by the increase in the number of stations, which is dominated by the increased use of stations in the south. If we divide the observation period into three different periods (2002–2011, 2011–2015.5, and 2015.5–2018.3), the average number of stations in the south is 1.7 for the first period, than doubles for the second period (3.4), and reaches 4.3 for the third period, while the average number of stations in the north increases from 5.2 for the first period to 6.2 for the third period. Thomas et al. 2018 [3] investigate the differences between R1 and R4 sessions and highlight some possible reasons that explain the formal error discrepancies between different periods.

There is no such variation in the position formal errors of the RDV sessions: the formal errors remain comparable over the period 2002.0–2018.3. This is because the RDV sessions have the VLBA network as a base of its network which is ten stations in the northern hemisphere. To this network, up to ten geodetic stations capable of recording VLBA modes were added at the beginning of the campaign, then up to six stations from 2009, the number of stations varying from session to session. In July 2009, the recording mode changed from 1-bit to 2-bit sampling.

3 Statistical Characterization of 3C418 Position Time Series

To obtain the type and the level of noise, we use the Allan variance. If $(x_i)_i$ are the measurements and τ the sampling time, the Allan variance at τ is defined by: $\sigma^2(\tau) = \frac{1}{2} < (\widehat{x_{i+1}} - \widehat{x_i}) >^2$. The type of noise is obtained by computing the slope of the Allan variance curve in a plot $(log_{10}(\sigma^2(\tau)), log_{10}(\tau))$. A slope of -1 indicates white noise, 0 indicates flicker noise, and $+1$ indicates random walk.

To be able to use the Allan variance, the time series have to be equally spaced. For this reason, the time series were first yearly averaged.

Figure 4 shows the Allan variance processed on yearly averaged time series of R1, R4, RDV, and all sessions time series. The plot points are all within the same range: the level and type of noise for each session types are very similar. But three points are not sufficient to determine significantly the type of noise.

Table 1 Type and level of noise determined by the Allan variance on weekly averaged time series.

Session type	Slope and sigma	
	Right Ascension	Declination
All sessions	-0.40 ± 0.09	-0.27 ± 0.08
R1	-0.21 ± 0.07	-0.15 ± 0.07
R4	-0.34 ± 0.08	-0.17 ± 0.02
Session type	Allan variance (7 days) in microas	
	Right Ascension	Declination
All sessions	87.14 ± 0.17	92.70 ± 0.18
R1	78.36 ± 0.16	91.12 ± 0.18
R4	142.60 ± 0.28	133.70 ± 0.27

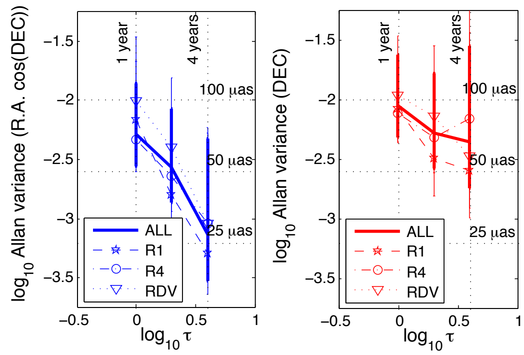

Fig. 4 Allan variance graphs processed on yearly averaged time series. All sessions, R1 sessions, R4 sessions, and RDV sessions.

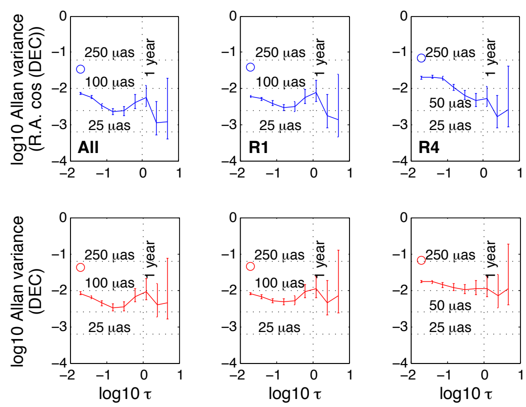

Fig. 5 Allan variance graphs processed on weekly averaged time series. Left: All sessions. Center: R1 sessions. Right: R4 sessions. The circle at $\tau = 7$ days indicates the standard deviation of the time series.

Figure 5 shows the Allan variance processed on weekly averaged time series of R1, R4, and all session time series. Other kinds of sessions, e.g. RDVs, do not occur frequently enough to compute a weekly average. Table 1 gives the type and level of noise determined by the Allan variance plot. For the R.A. component, the slopes vary between -0.21 ± 0.07 for the R1 sessions and -0.34 ± 0.08 for the R4 sessions, and for the DEC component, between -0.15 ± 0.07 for the R1 sessions and -0.17 ± 0.02 for the R4 sessions. These slopes give a similar conclusion for the type of noise—the time series exhibit a flicker noise. As expected from Section 2, the level of noise of the R4 sessions is higher than the level of noise of the R1 sessions for both components. This seems to impact the Allan variance plots for sampling times lower than $\tau = 1$ year, as seen in Figure 5.

4 Discussion: Temporal Evolution of 3C418

The position time series of 3C418 are remarkable because of the change in behavior. To track where the evolution impacts the statistical characterization of the source, we studied the time series on different time periods. As an initial time period, we take 2002.0 to 2006.3 and process the Allan variance on this period. Then we add six months of data and process the Allan variance on this new period. We follow the same procedure until we reconstruct the entire series. Each Allan variance processing provides the slope of the Allan variance for R.A. and DEC that determine the type of noise and the Allan standard deviation at 64 weeks for R.A. and DEC that determine the level of noise (see Figure 6). In Figure 6, we added the regular standard deviation for comparison.

The conclusions are similar for both components. The type of noise is determined as white noise until late 2016 when the type of noise shifts to flicker noise. At the same time, the Allan standard deviations as well as the standard deviations increase rapidly. The standard deviations are between 180 µas and 200 µas when processed on the entire time series, and are between 120 µas and 140 µas when processed on the period 2002.0–2006.3.

The source 3C418 is a source used as a base in geodetic session scheduling: it was initially chosen because it was a stable and compact source. If evaluated now, the source statistical characterization would not make a good candidate.

5 Conclusions

This study shows that the statistical characterization of sources is influenced by the level of noise of the time series. This level of noise depends on the type of sessions used to observe the sources: R4 sessions have position formal errors larger than R1 sessions, which have larger formal errors than RDV sessions.

Another difficulty for determining the type of noise is the unpredictable temporal evolution of the source. This study showed that 3C418 had a stable position (stable means in this context a predictable position not

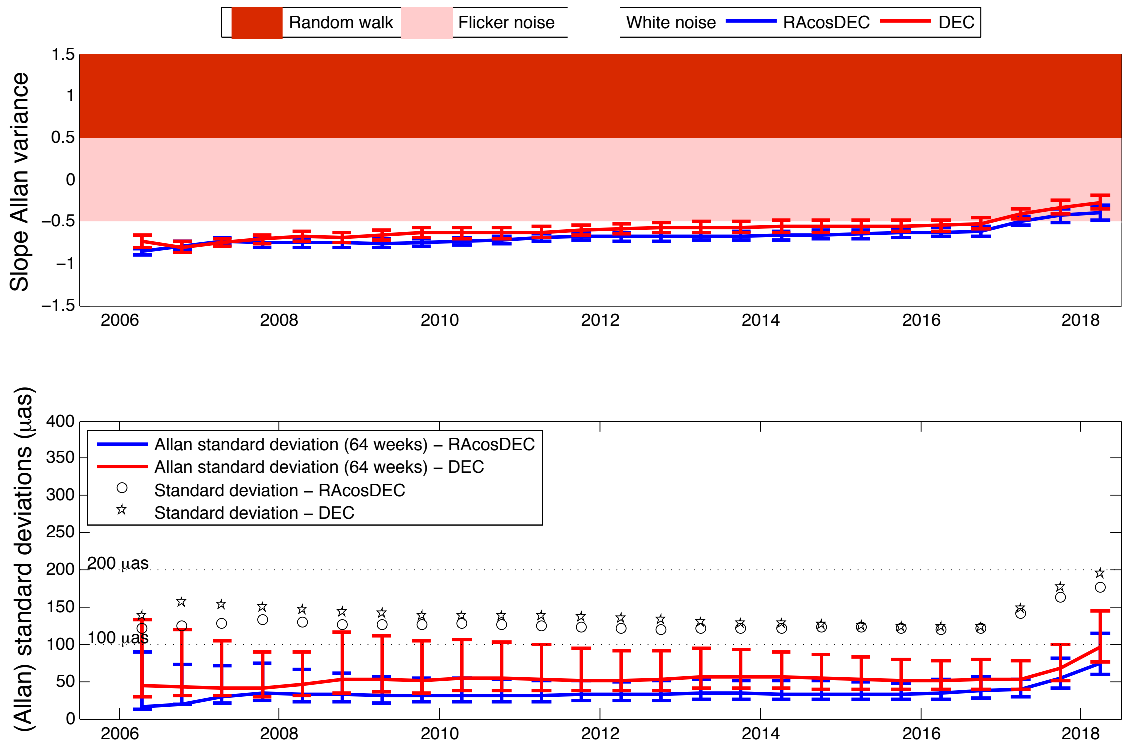

Fig. 6 Level and type of noise of 3C418 in function of the period. The initial period is 2002.0–2006.3 (first points on the left side of the graphs). Each additional points correspond to the previous period incremented by six months of data.

changing with time) from 2002 until 2016, when the source position changed abruptly.

This demonstrates we need to observe sources more often and regularly to monitor them more precisely.

This method could be developed as a tool to monitor source time series type and level of noise. To be complete, this tool should also provide quantities as these:

1. level of noise using the Allan variance at different sampling time, type of noise using the Allan variance on regularized series averaged on different periods from 7 days to 1 year (this is significant when the source is sufficiently observed);
2. level of noise using the regular standard deviation, drift of the time series,... (quantities that could be computed even with a low number of observations);
3. Structure Index SI from Fey & Charlot 1997 [4], time series of flux values,... (quantities to indicate the physical nature of the source).

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